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Future Applications of Smallsats Towards Remote Sensing

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Abstract

Humankind is no longer strictly earthbound. Through the use of modern technology, future space exploration will be so extensive, and the data collection anti return so comprehensive, that a virtual human presence in the universe will be created, We will be linked to the far reaches of our solar system, and beyond,

Launch frequency will be increased to the point where tens of launches per year will be conducted, compared to the launches per decade of today's space exploration, Armadas of individual spacecraft as well as spacecraft networks or constellations will be used to execute exciting missions and amass the data that will bring about the realization of this vision of space exploration for the 21st century, On the road to achieving this vision, a technological revolution will occur. We are on the brink of this revolution — and the New Millennium Program will initiate it,

In addition to scientific and technological advances, social and educational benefits will result, Space exploration in the 21st century will lead to a global strengthening of the world economy as new technologies and capabilities are developed, With new knowledge and expanded communications, positive feedback into our educational programs will also be realized,

Exploration in the 21st Century

Space exploration in the 21st century will be significantly different from what we see today, particularly in the robotic space science sector, Spacecraft will be significantly smaller — weighing less than 100 kg — highly autonomous; self-navigating, controlling, and correcting; and more frequently launched. These armadas of spaceships will fly individually, in constellations and in networks, returning a continuum of data that will create a virtual presence in the universe, This departure from today's large multifunctional ships is enabled by the recent explosion in functional capability in digital electronics, where functional density has been doubling every year and a half for the past decade,

In the 1960s and 1970s, spacecraft electronics were mainly discrete component based, so that as the spacecraft functionality increased, so did its component count. Thus, weight, volume, and power grew linearly, In the beginning, discrete component reliability was limited, and redundancy was used to achieve the required lifetime for multiyear flights, Round-trip communications time dictated the nature and expansion of onboard autonomy and fault protection and correction, Size, weight, power, design, development, and cost all grew linearly with increasing capability, Launch vehicle capability was plentiful and launching these spacecraft weighing many thousands of kilograms was well within the capability of the launch vehicles under development, Then, with the basic transportation capability in hand to visit other planets, it become cost effective to maximize the science return from each mission, within cost and schedule constraints. The infrequent launch opportunities were also a driving force to accomplish as much science as possible for each mission, and spacecraft with the capabilities to execute 20 or more science experiments were developed,

Space exploration in the 21st century will recognize and take advantage of the current solid-state electronics and use today's sophisticated technology and the commercial computer industry's developments to fly small, fully autonomous spacecraft, The exorbitant cost of large launch vehicles will be eliminated by flying microspacecraft and microinstruments; ground operations costs will be radically reduced through the use of self-tending spacecraft,

The New Millennium Program

The National Aeronautics and Space Administration (NASA) has established the New Millennium Program to enhance the development and flight readiness of those technologies deemed most necessary for 21st-century space exploration and Earth observation missions. The process has been to clarify the science vision for the 21st century through the missions to be accomplished, using the science vision to specify the needed technologies, and then construct a series of technology-validation flights to be conducted before the end of this century, The technologies to enable future missions will thus be ready to use when they are needed, The capability needs identified for 21 st-century space exploration are summarized in Table 1,

Table 1. Summary of Key Capability Needs for the 21st Century

Capability Category	Key Capability Needs
Microelectronics	• On board high-speed data processing • Miniature deep space communications
Instruments and Probes	• Affordable advanced microinstruments • In situ analysis • Affordable small-body landers • Sample acquisition • Balloon technologies, surface mobility
Flight Systems	• Onboard autonomy • Precision control of spacecraft clusters • Operations at distances up to 5 AU • Affordable stationkeeping of multiple spacecraft • Efficient operation of spacecraft networks • Fast and flexible access to the entire solar system
Mechanical and Thermal Systems	• Thermal control in high-temperature environments • Long-life cryogenic systems • Networks of small spacecraft
Energy Sources and Storage	• Efficient non-nuclear energy collection and storage

The next step is to seek out emerging technologies that can provide solutions, and then select the highest priority technologies (Figure 1). A wide range of emerging technologies promise to provide the capabilities required to realize the vision of space expiration and Earth observation, Table 2 summarizes these promising technologies, arranged by capability needs, Many of these technologies were identified through a variety of NASA and space science community studies,

Table 2. Enabling Technologies for Space Exploration in the 21st Century

Capability Needs	Enabling Technologies
Microelectronics	• Integrated microelectronics, high-density packaging • Advanced flight computers • On-chip massively parallel and neural circuits • Integrated, high-efficiency telecommunications electronics • Radio frequency phased array antennas • High-density solid-state recorders • Hybridized power management electronics
Instruments and Probes	• Microelectromechanical systems (MEMS) • Integrated microsensors and instruments • Integrated microlanders and free-flyers • Sample acquisition and manipulation • Telepresence and machine dexterity • Analytic surface science lab • Next-generation focal plane arrays • Low-temperature optics • Starlight cancellation technology • Precision stationkeeping and constellation attitude control • Long-range laser metrology and laser radars
Flight Systems	• Autonomous navigation and pointing • Onboard control of science data collection • Self-commanding and monitoring software architectures • Autonomous stationkeeping • Autonomous, distributed ground systems • Cross-cutting architectures and interfaces • Automated planetary entry and hazard avoidance • Low-cost and reusable launch vehicles • Clean solid propellants • Hybrid propellant motors and stages • High specific impulse onboard propulsion • Microthrusters and arcjets • Innovative aerovehicles
Mechanical and Thermal Systems	• Large area, low-mass deployable and flexible structures • Advanced thermal control • Long-life cryocooler systems • Low-mass and multifunctional structures

	• Phase change memory materials • Smart structures for vibration suppression • Embedded sensors • Small, low-mass reaction wheels
Energy Sources	• Large-area, low-mass solar energy collectors • Advanced solar cells • Advanced energy conversion systems

NASA's New Millennium Program plans the first technology-validation flights in late 1997 and early 1998, The yearly flights will validate the technologies needed to enable 21st-century capabilities. The New Millennium Program is the investment needed to realize our vision of future exploration — armadas, networks, constellations, spacecraft-on-a-chip designs, monthly launches, and the creation of a human virtual presence extending throughout the universe.

The United States' "pipeline' of technology (Figure 2) is fed by NASA, the Ballistic Missile Defense Organization, the Advanced Research Projects Agency, other government agencies, industry, and universities, The New Millennium Program will dip into this pipeline to select vision-driven technologies for flight validation, This high-leverage utilization of the nation's technology investment will bring these needed technologies to a flight-readiness condition years earlier than could otherwise be achieved, The accelerated availability of key technologies will also accelerate the science achievements of 21st-century space exploration and Earth observation missions.

The vision, the technologies, and the technology -validation flights are tightly connected within the New Millennium Program (Figure 3). The chain is logically connected and addresses a high-level, long-range vision for the next century. Unlike other technology-validation flight programs, the selected technologies are based on the requirements for fulfilling the vision, rather than the technology readiness — the situation is one of mission-needed technologies, not technologies looking for a mission.

While the New Millennium validation flights are specified by the technologies, they will also be structured to provide science value — the science as well as selection criteria will take into account technology, cost, schedule, and other programmatic considerations, Similarly, the technologies established from the vision will be selected with their commercialization value in mind, and finally, the vision itself will have significant value for society.

High-Priority Missions

Comet Sample Return

Comet sample return missions (Figure 4) form a category of high-priority missions focused on our solar system and grouped within the unifying theme of "Our Planetary Neighbors, " Characterization of the primitive materials of which comets are composed will shed light on the origin and evolution of the solar system, The envisioned mission implementation includes the selection of an appropriate landing site following an orbital survey, in situ study, selection and collection of local samples, and return of samples to Earth through a direct atmospheric entry,

To carry out such a mission, advances in autonomous operations, low-mass structural materials and high specific impulse propulsion will be required, High-capability, low-mass onboard computers and new approaches to sample handling and preservation are also needed capabilities, *Extrasolar Planetary Imaging*

An example of a high-priority mission to explore the universe is a free-flying interferometer constellation capable of imaging extrasolar planets (Figure 5). Such a constellation could detect Earth-like planets and provide information clarifying the origin and evolution of planetary systems in general,

Based on a widely spaced constellation of three or more spacecraft with precision formation control, this mission would require precision pointing and control of a constellation, nanometer-scale interspacecraft metrology, and accurate stationkeeping. Quiet spacecraft structures, low-thrust propulsion, and low-mass, high-quality optics are also needed capabilities to implement a free-flying interferometer.

Key Capabilities Enable **the Vision**

Increased capability, reduced cost, and increased flight rate will be achieved by using smaller launch vehicles that are enabled by microspacecraft and microinstruments (Figure 6). It will also be necessary have shorter flight times and to decrease the size of mission operations staff through the use of intelligent flight systems,

A Roadmap for Microspacecraft Development

We could reduce spacecraft mass and reduce costs by miniaturizing spacecraft components, However, miniaturization alone would reduce our capabilities to obtain the science data required to fulfill our vision for the 21st century (Figure 7), Through the infusion of new technologies, such as innovative architectures and highly capable microdevices, we can develop new concepts that will actually increase our capabilities beyond what is currently possible, while simultaneously reducing mission costs,

Spacecraft Mass Decrease

Because of the importance of spacecraft weight in the New Millennium Program, a chart illustrating how spacecraft mass has changed over time was developed (Figure 8) showing the historical increase of spacecraft mass during the 1960s, 1970s, and 1980s, and the start of decreasing spacecraft mass in the late 1980s early 1990s. Projections for the future clearly show a rapid decrease in mass, made possible by the dramatic reduction of the size of the digital electronics, The Clementine spacecraft stands out as an example of a significant mass reduction enabled by the technology developed in prior years, and the continued decrease in spacecraft mass in New Millennium indicate the continued development of this technology in the future,

Capable Microspacecraft Flight Avionics

New chip technologies allowing “three-dimensional” stacking of microelectronics are examples of emerging technologies that can significantly reduce the mass and size of spacecraft subsystems (Figure 9), This new approach reduces multiple cards of electronics to single-chip stacks and can be applied to some of the massive spacecraft subsystems, including onboard computing, power, and telecommunications systems, “These novel stacking and interconnect technologies enable new integrated computing architectures and automated design methodologies, promising reduced design costs, In comparison to the Mars Pathfinder flight computer, this technology reduces the mass and volume by a factor of 100, with a 20-fold reduction in power, while enhancing the onboard computing capability,

Powerful Microinstruments
Emerging microelectromechanical systems (MEMS) Technology (Figure 10) promises orders of magnitude reduction in the size of a variety of instruments for space exploration and Earth observation. Following in the footsteps of the microelectronics revolution, this technology extends on-chip capability beyond electronics to include mechanical and optical functionalities. MEMS technology enables new classes of microinstruments that make in situ measurements a practical alternative to costly sample return for a variety of analytic measurements of planetary surfaces and atmospheres, as well as small-body investigations,

Integrated mitt'osensor packages are small enough to be deployed as networks of microlanders (shown schematically in the center of the figure) anti orbiters offering global planetary coverage, For example, a network of microseismometers (upper left) can provide information on global seismometry and could map the interior structure of planets, Similarly, networks of micrometeorological sensors such as pressure sensors (upper right) and hygrometers (lower right) can be used to investigate planetary climate and complex atmospheric dynamics,

Instrument Miniaturization
Small spacecraft require smaller instruments, Orders-of-magnitude reduction in instrument mass and volume are anticipated through the infusion of new miniaturization technologies, A typical instrument deployed during the "flagship" era is represented by the Microwave Limb Sounder carried by the Upper Atmosphere Research Satellite, launched in 199l (Figure 11), At 250 kg, it literally towers over the human in the picture, in contrast, the Planetary Integrated Camera Spectrometer, incorporating multiplexed foreoptics, low-mass composite structures, and advanced focal plane technologies, has a mass of only 5 kg.

Future instruments incorporating MEMS, permitting on-chip integration of sensors and electronics, will reduce some instrument to mere grams, A concept for a complete free-frying magnetometer with onboard power, data processing, and telecommunications, has a mass of only 100 gm. The realization of such "spacecraft-on-a-chip" concepts will enable swarms of free-flyers capable of mapping complex and dynamic systems in space,

A Roadmap for Low-Cost Mission Operations Development

The costs of operating spacecraft are a significant portion of the costs of the mission, Mission operations costs could be reduced by simply flying fewer missions, but this direction is opposite to our vision, which calls for greatly increased numbers of missions, "How, then, can we afford to operate 30 or more missions at a time? Through an infusion of technology and new ways of doing business, we will be able to use intelligent flight systems and autonomy to reduce the number of people required to operate and monitor spacecraft — thereby decreasing operations costs (Figure 12),

Intelligent Flight Systems and **Autonomy**

Revolutionary new concepts for ground operations take advantage of the “economy of scale” of large numbers of semiautonomous spacecraft (Figure 13). Assuming that, at any given time, most spacecraft are healthy and require no ground intervention, the costly approach of a dedicated operations team for each spacecraft can be transformed into a low-cost “on-call’ system that provides service only when needed, This approach also increases the capacity of NASA’s Deep Space Network (DSN) to handle a much larger number of missions simultaneously,

The concept includes a low-fidelity beacon network to monitor messages from the spacecraft that are limited to four simple options: ‘I’m OK”; “Problem detected and resolved ‘; “I’m ready for normal servicing’; and the occasional "Help!" The high-fidelity DSN is used only when received — to receive science data, to provide normal service, or to provide human intervention in an emergency situation beyond the resolution capabilities of the spacecraft,

This paradigm shift can be viewed as the equivalent of making an emergency room available to a community, rather than having a complete medical team in each home,

Autonomous Optical Navigation

Current navigation for deep space probes is based on trajectory determination and correction through ground-based measurements and calculations. In the departure phase, the launch vehicle injection errors are determined by radio tracking of the spacecraft, making range and range rate Doppler measurements, This data type is used to calculate the required spacecraft maneuver to place the spacecraft on the desired flight path to the targeted planet,

As the spacecraft continues its journey about the Sun, its heliocentric path is determined again by Earth-based tracking of range and range rate. Here again, the required trajectory corrections to place the spacecraft on the desired encounter path are calculated on the ground for subsequent transmission and execution on the spacecraft, As the spacecraft approaches the target body, ground-based tracking data are augmented with optical navigation taken by the spacecraft and transmitted to the ground, These two data types are combined on the ground to calculate the maneuvers required by the spacecraft to acquire the desired target position,

In the future, these navigation functions will all be performed on the spacecraft without ground measurements and calculations (Figure 14), 1 he departure phase will be through collecting range and range rate data using optical sensors onboard the spacecraft, These data will be sufficient to calculate the corrections needed by the spacecraft, and their “execution commands and sequence onboard the spacecraft, During the heliocentric cruise phase, optical measurements of known asteroids will be taken to determine the spacecraft's position and velocity for trajectory determination. These data will be combined with the known target body ephemeris to determine the trajectory corrections needed to set up the mission's target body encounter phase.

Thus, future missions will no longer depend on ground-based measurements for either orbit determination or correction, All of this onboard capability will result in reductions in the ground support staff, a factor of significant importance when launch rates are as high as once per month,

Technology for the 21st Century

The vision for space exploration and Earth observation in the 21st century is characterized by exciting missions at significantly reduced cost and greatly increased launch frequency, This vision cannot be implemented today because of gaps in our capabilities, In some cases, the capability is simply not available; in others, it is not available at an affordable cost ,

Thus, the first step in realizing the vision is the identification of these capability needs. Technology is advancing at an ever-increasing rate, and many of the emerging technologies provide potential solutions for the capability needs. The second step towards realizing the exploration vision is to identify technologies that provide the required capabilities at an affordable cost, Finally, the most rapid advances can be achieved by focusing on technologies offering the greatest impact on exploration opportunities for the 21st century,

This section provides a roadmap connecting the NASA vision for the 21 st century with the highest priority technologies to achieve this vision,

Technology Selection Process

Selection criteria can be used to identify the highest priority technologies from among the range of emerging technologies that will enable future missions (Table 3). Although a steady evolution in technology advances might eventually enable the next generation of space exploration and Earth observation missions, the timely development of key breakthrough technologies can accelerate this process to bring about a revolution in exploration in the early 21 st century, *Table* 3. *Selection of Highest Priority Technologies for Flight Validation*

Lead-ahead technologies emphasizing capabilities that:

- Contribute significantly to reducing the cost of future science missions
- Increase the relative scientific capability of these missions
- Enable frequent space missions
- Address the ‘tall poles” for post-2000 missions
- Enable new approaches to space exploration

Since one of the primary drivers is the affordability of future space missions, a key characteristic of high-priority technologies is their ability to significantly reduce the cost of future missions. Similarly, the technologies must enhance the relative scientific value of the missions, and provide the ability to launch missions at a greatly increased frequency.

Ultimately, it is critical to address the "tall poles' for the desired **post-2000** missions — those capability barriers determined to be the most difficult to overcome, Breakthrough technologies can enable entirely new approaches, opening new opportunities for an intense phase of space exploration and Earth observation at an affordable cost,

Candidate High-Priori/y Technology

Table 4 summarizes a first cut in identifying key breakthrough technologies offering the greatest impact on 21 st-century space exploration and Earth observation opportunities, Significant savings in mass are offered by recent advances in high-density electronics stacking technologies, This new approach reduces multiple cards of electronics into single "three-dimensional" chips, and can be applied to onboard computing and power and telecommunications systems.

Table 4. Candidate High-Priority Technology

Microelectronics

- Advanced flight computer with MCMS and 3-D chip stacking
- Integrated power-management electronics
- Miniature deep space RF and optical telecom
- Lithium ion batteries

On board Autonomy

- Autonomous GNC and closed-loop feature tracking
- Self-commanding and health monitoring
- Information system architectures for ground and space commonality

Microelectromechanical Systems (M EMS)

- MEMS design and modeling
- MEMS navigation sensors
- Microlander with integrated microsensor package
- Integrated free-flying magnetometer

Instruments

- Planetary integrated camera/spectrometer
- Active pixel sensor
- Miniature coded-aperture X-ray imaging spectrometer
- Kilometric optical gyro and precision metrology
- Autonomous constellation stationkeeping

Advances in onboard autonomy promise significant reductions in operations costs, Navigation, control, and health-monitoring functions can be migrated to autonomous onboard systems, eliminating the need for a large ground staff. A major technological revolution that is just now emerging is based on the ability to integrate multiple functionalities (including mechanical and optical functionalities) on-chip with the electronics, These multifunctional MEMS promise miniaturization of a wide variety of instruments and spacecraft subsystems.

Miniaturization technologies can reduce instrument size by orders of magnitude without loss in capability, and technologies to enable kilometer-baseline free-flying interferometers promise breakthroughs in imaging resolution, extending our view to other solar systems,

Exploration in the 21st Century

Our vision for the 21st century is a compelling one, incorporating access to new frontiers and great expansion of our scientific understanding (Table 5). With networks of landers on Mars and Venus, clusters of probes mapping planetary ionospheres and magnetospheres, spacecraft returning samples from asteroids and comets, and constellations of spacecraft peering into neighboring solar systems, we will truly be able to bring the solar system back to Earth, creating a virtual presence in space, Two new mission approaches are required — individual spacecraft fleets, and constellations and networks of spacecraft,

Table 5. Exploitation in the 2 Ist Century

The vision — establish a virtual presence in space and access new frontiers to expand our scientific understanding of the universe,

This vision can be realized through two new missions approaches:

- A fleet of individual spacecraft to explore a diversity of targets
  - —Inner and outer planets
  - —Small bodies throughout the solar system
- Spacecraft networks to address dynamic and complex systems
  - —Constellations of spacecraft to detect and image neighboring solar systems
  - —Planetary networks to characterize interiors, surfaces, and atmospheres
  - —A network at the Sun to characterize and monitor solar activity

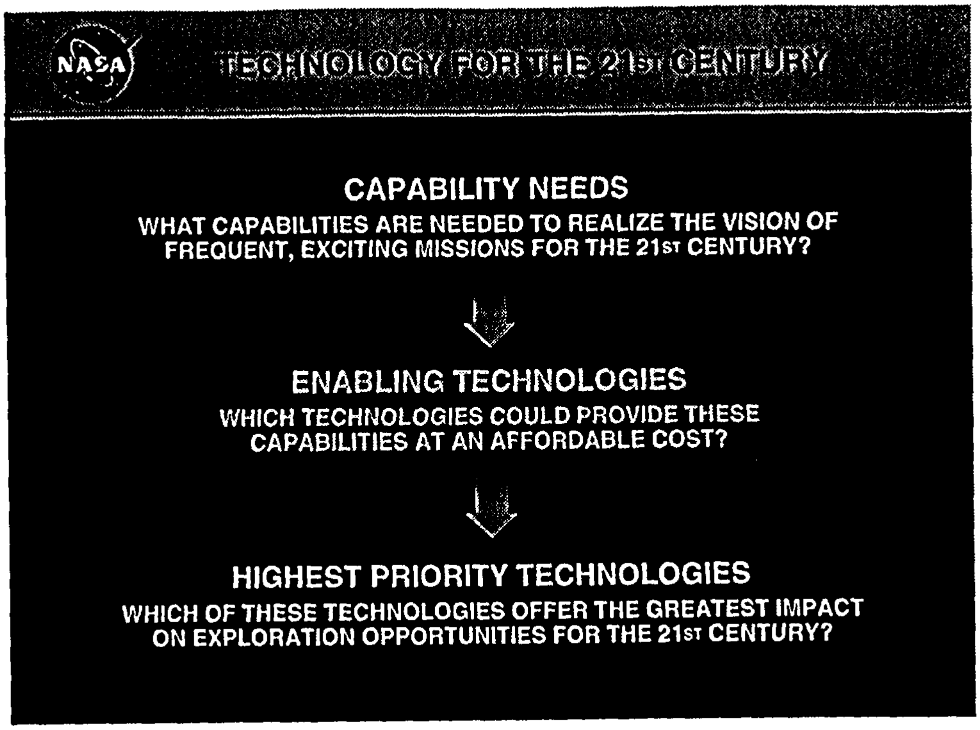
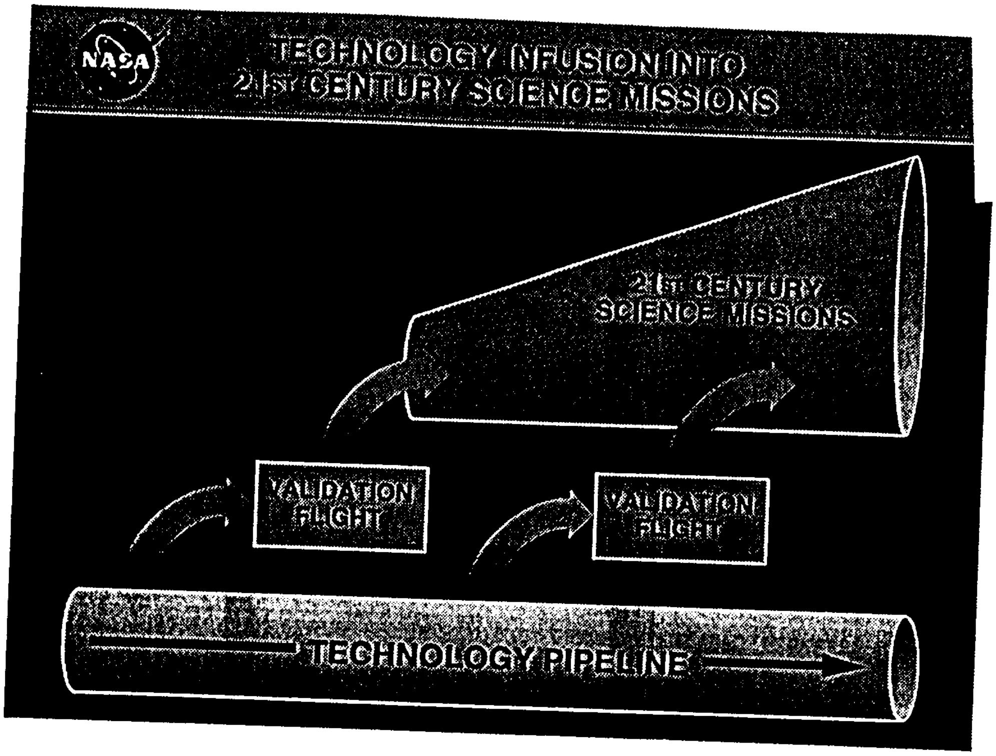


Fig. 1

After identifying the key capability needs, the next step is to seek out "emerging technologies that can provide solutions at an affordable cost.

Fig. 1



- The technology pipeline exists and is flowing full.
- Vision-driven technologies will be selected from the pipeline and placed into validation flights to enable the missions of the 21 st Century.
- These validation flights are a high-leverage utilization of both NASA's and the Nation's investment in technology.
- These validation flights will bring the needed technologies to a flight readiness condition several years earlier than otherwise.
- The availability of these key technologies will accelerate the science achievement of the 21st Century space and earth science missions.

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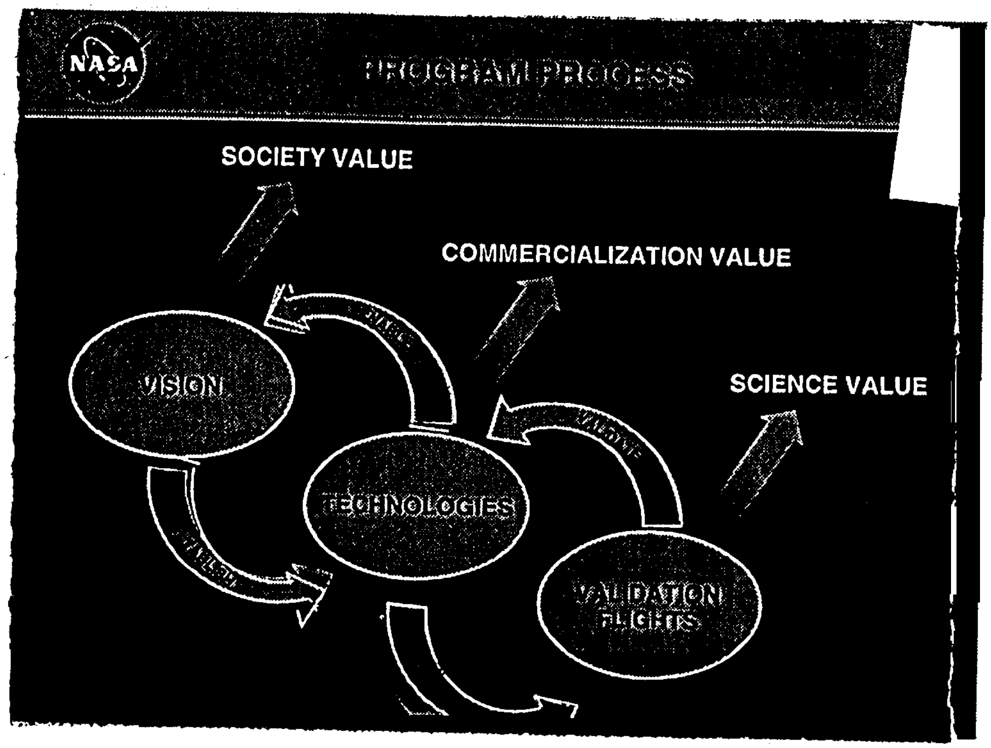


spell out

tightly

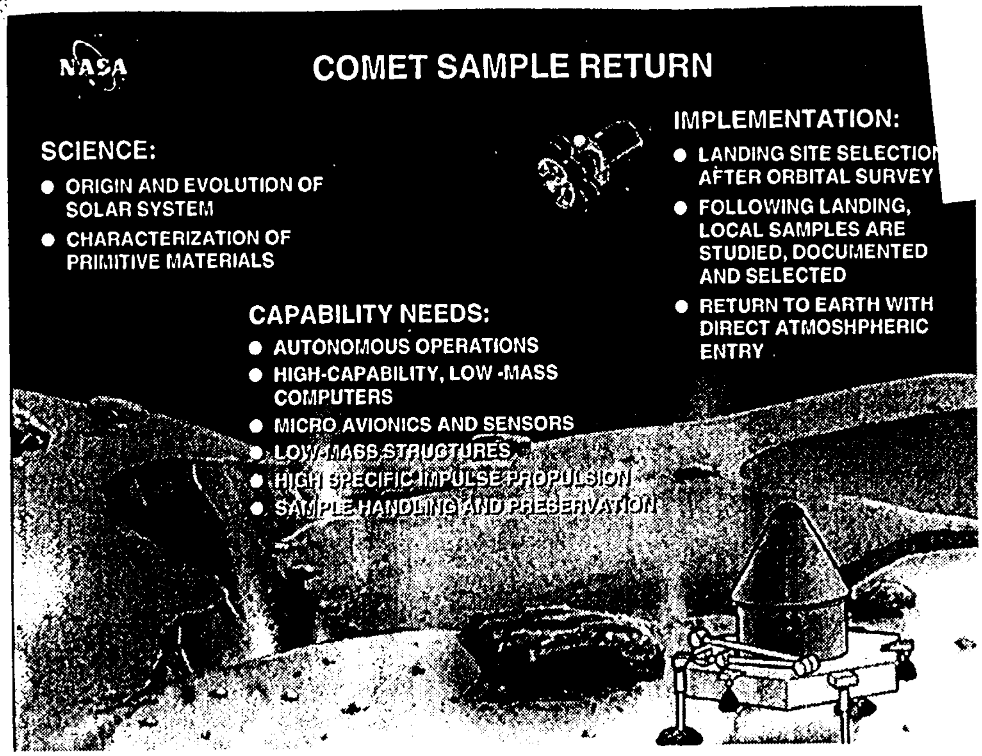
highly is an adverb. I think hyphens are only used with adjectives and nouns when the combination is used as an adjective

wt

The vision, technologies, and validation flights are highly-connected within the NMP. Unlike other validation flight programs, the selected technologies are based on the vision needs rather than the technology readiness. It is mission-needed technologies, not technologies looking for a mission.

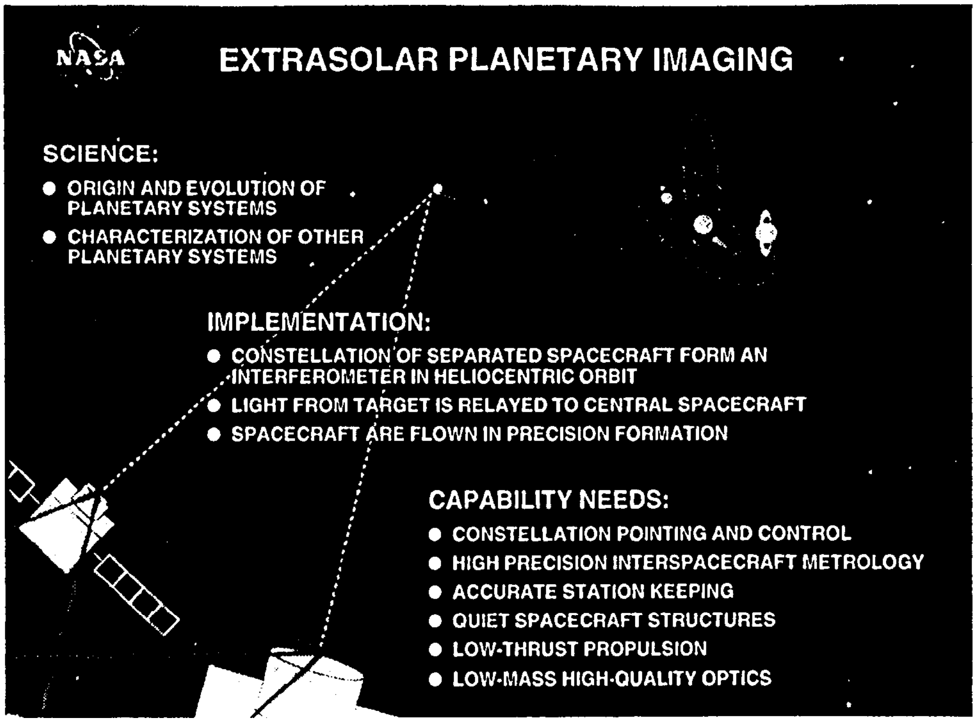
The chain is logically connected and addresses a high-level, long-range vision for the New Millennium next century.

fig. 3



A comet sample return is an example of a high-priority mission focused on our solar system and grouped within the unifying-theme, "Our Pianetary Neighbors." Characterization of the primitive materials of which comets are composed will shed light on the origin and evolution of the solar system. The envisioned mission implementation includes the selection of an appropriate landing site following an orbital survey, the in-situ study, selection and collection of local samples, and their return to Earth through a direct atmospheric entry.

To carry out such a mission, advances in autonomous operations, low-mass structural materials and high-specific impulse propulsion will be required. High-capability, iow-mass on-board computers and new approaches to sample handling and preservation are also needed capabilities.



An example of a high-priority mission to explore the universe around us is a free-flying interferometer constellation capable of imaging extrasolar planets. Such a constellation could detect other Earth-like planets and provide information clarifying the origin and evolution of planetary systems in general.

("widely" is an adverb)

Based on a widely-spaced constellation of three or more spacecraft with precision formation control, this mission requires precision pointing and control of a constellation, nanometer-scale interspacecraft metrology and accurate station keeping. Quiet spacecraft structures, low-thrust propulsion, and low-mass, high-quality optics are also needed capabilities to implement a free-flying interferometer.

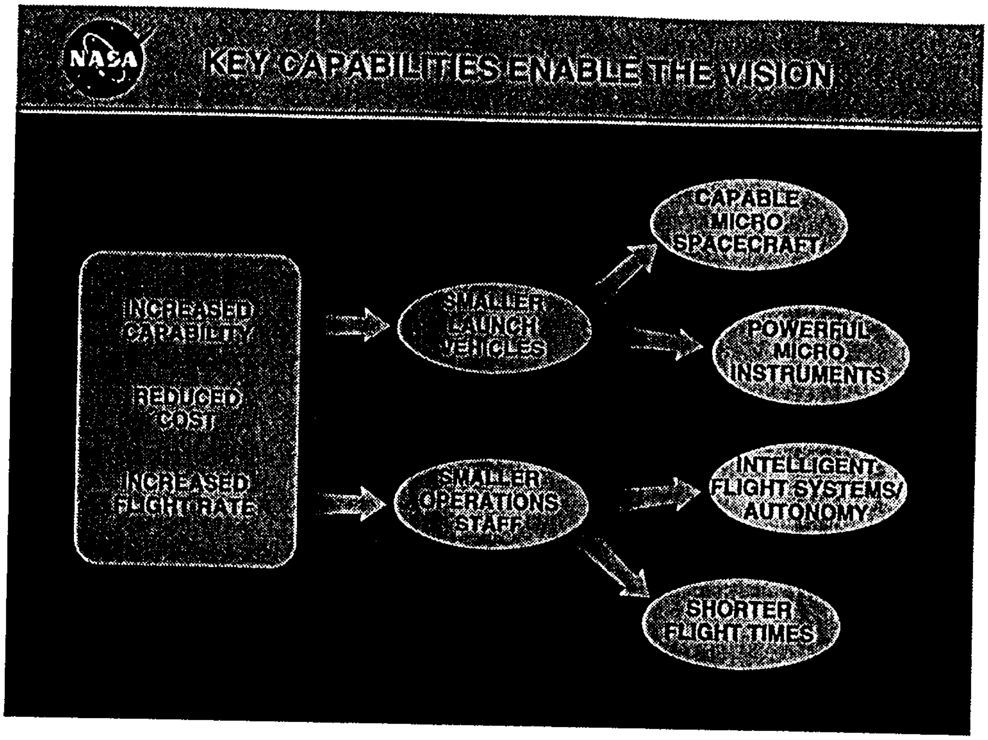


Fig 8

Increased capability, reduced cost and increased flight rate will be achieved ~~through~~ by

- **using smaller** launch **vehicles enabled by microspacecraft and microinstruments,** and by
- **decreasing the size of mission operations staff.** through the use of **~~and-replacing them with~~ intelligent fight systems, and** shorter flight times.
- **~~decreasing flight times~~.**

Fig 6

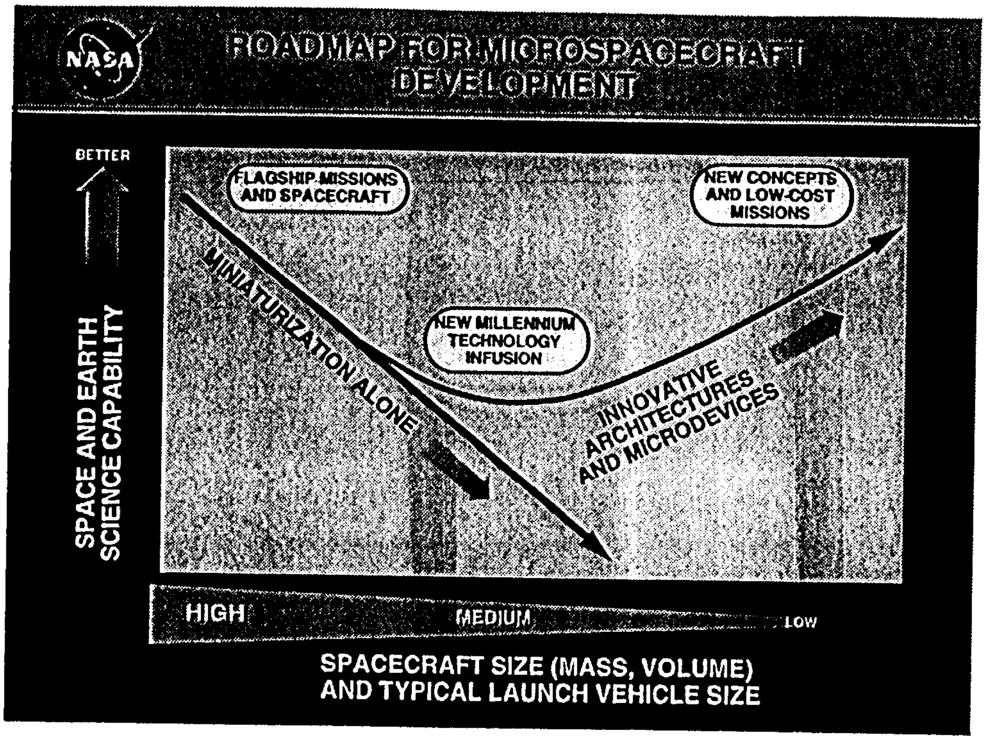


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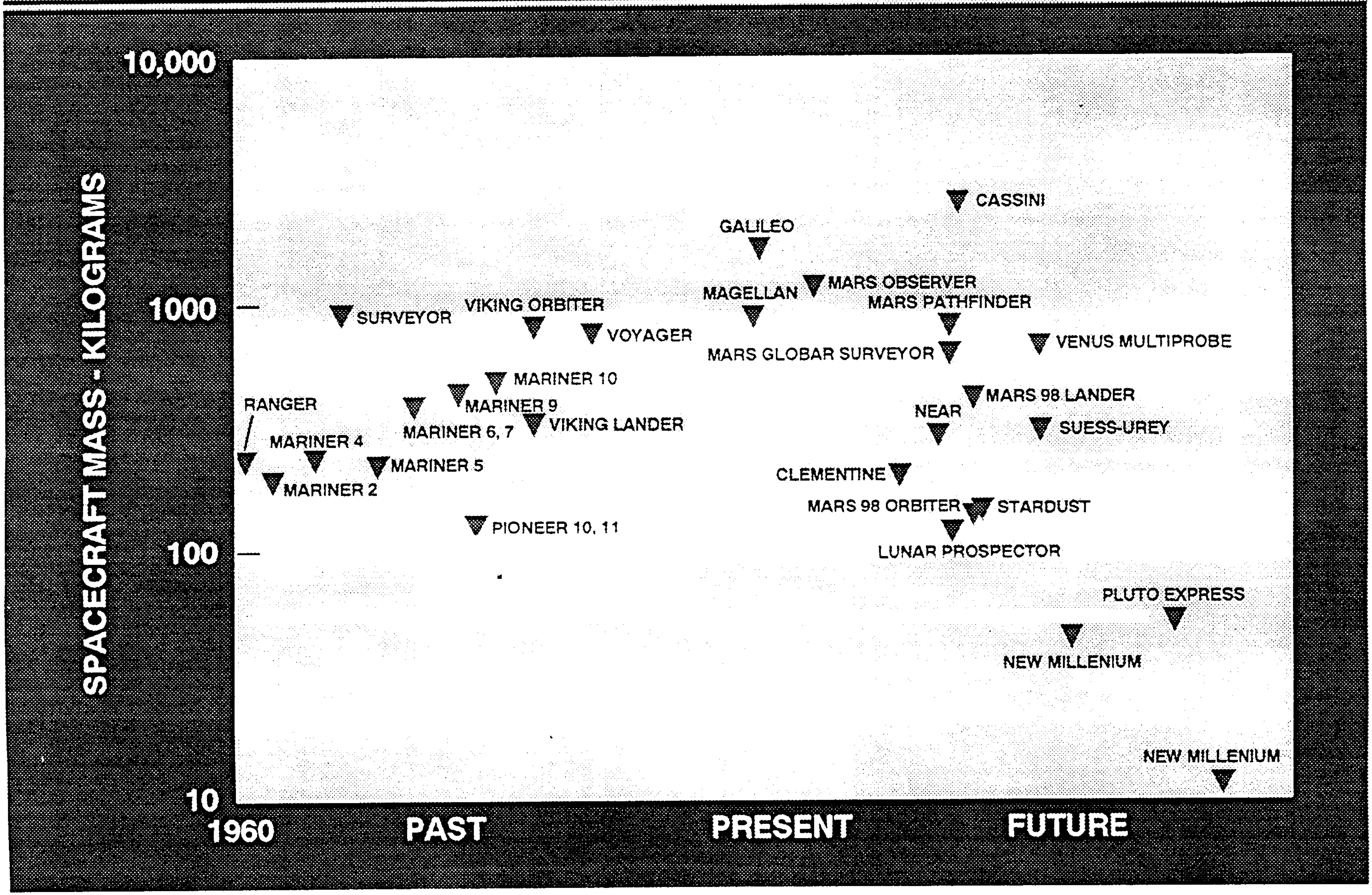
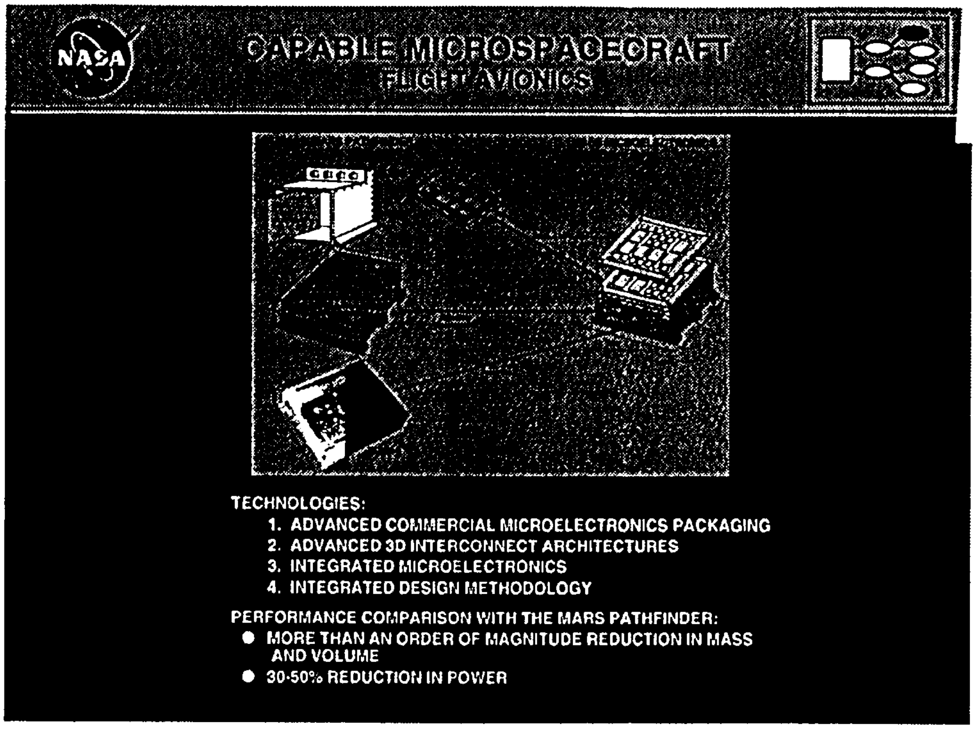
FIG 7

SPACECRAFT DRY MASS vs. TIME



(F8) Fig 8



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are example ies

New chip technologies allowing "three-dimensional" stacking of microelectronics ~~is an example of~~ emerging technology that can significantly reduce the mass and size of spacecraft subsystems. This new approach reduces multiple cards of electronics to single-chip stacks and can be applied to some of the massive spacecraft subsystems including on-board computing, power, and telecommunications systems. These novel stacking and interconnect technologies enable new integrated computing architectures and automated **design methodologies, promising reduced design costs.**

In comparison to the Mars Pathfinder flight computer, this technology offers more than an order of magnitude reduction in mass and volume and a 50% decrease **in power required, while enhancing the on-board computing capability.**

F9

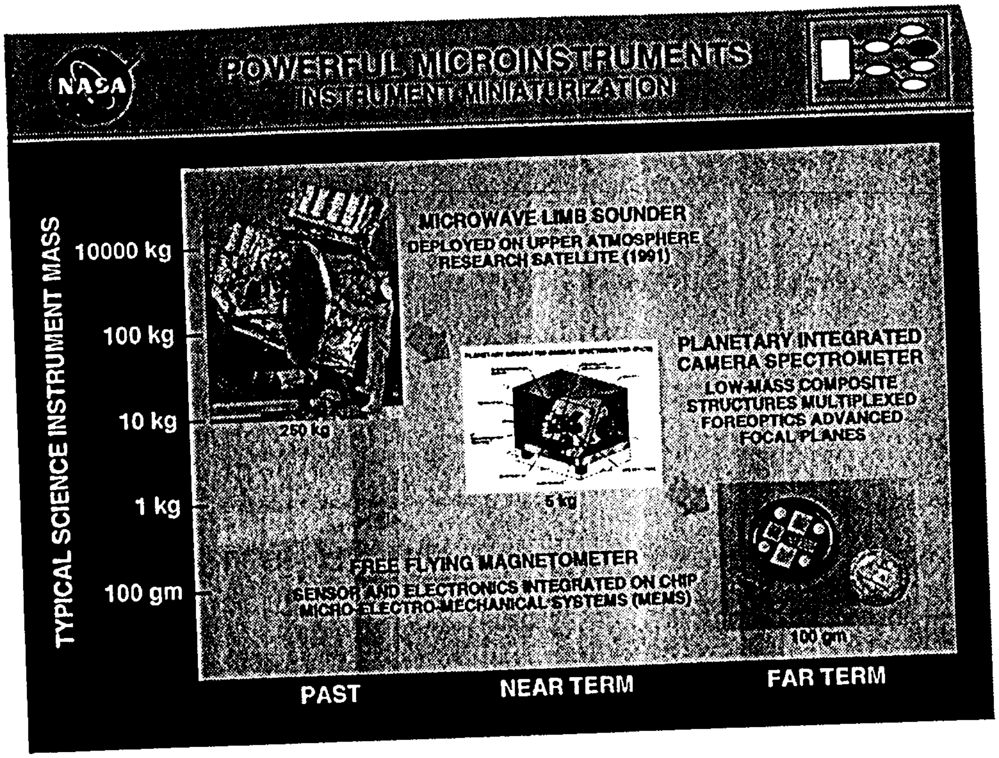

Fig. 11

concomitantly

Smaller spacecraft require smaller instruments ~~and~~ orders of magnitude reduction in instrument mass and volume are anticipated through the infusion of new miniaturization technologies.

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technologies on-chip integration of

Future instruments incorporating micro-electro-mechanical systems (MEMS), permitting sensors and electronics ~~integrated-on-chip~~, will reduce some instruments to mere grams. A concept for a complete free-flying magnetometer with on-board power, data processing “spacecraft-on-a-chip” has a mass of only 100 gm. The realization of such concepts will enable swarms of free-flyers capable of mapping complex and dynamic systems in space.